Open charm photoproduction with generalized γA-FONLL at LHC and EIC

Anna Staśto

Penn State University

Outline

- Why study open charm in **ultraperipheral collisions (UPC)**: probe of nuclear structure and gluon density in the nucleus
- **GγA-FONLL** framework: generalized photon-nucleus FONLL for UPC
  - Open charm production cross section in FONLL approach
  - Photon flux. **Electromagnetic dissociation**
- GγA-FONLL prediction for D^0 production in UPC at LHC and comparison with CMS data
- **Diffractive** cross section in UPC AA using LTA approach
- Predictions for **UPC proton-nucleus** and **EIC**
- Conclusions

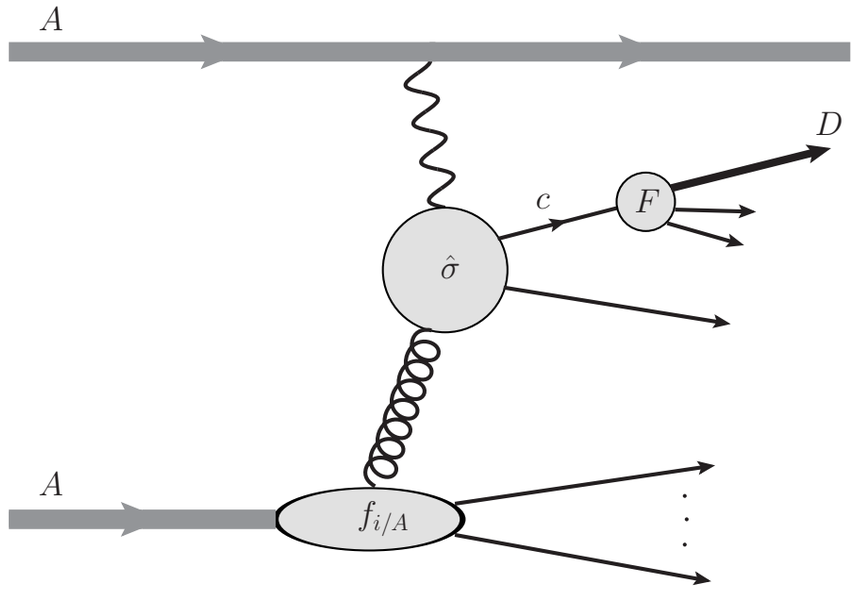
Gian-Michele Innocenti,Matteo Cacciari, AS, arXiv:2506.09893
Vadim Guzey, Gian-Michele Innocenti, Mark Strikman, AS, work in progress

UPC with hard scale: open charm photoproduction

Charm production in UPC AA

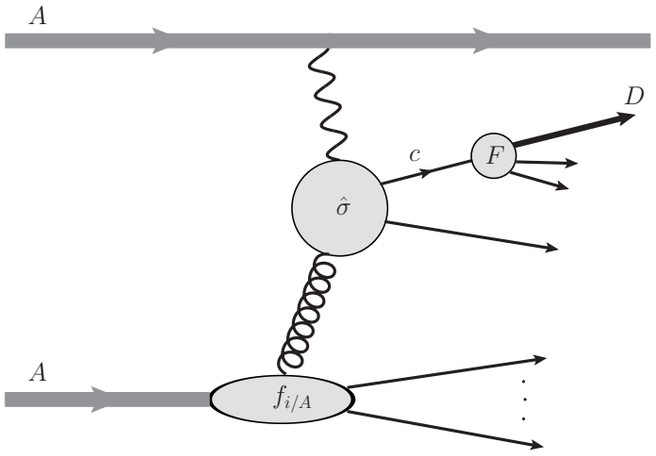
$$A\,A \to A\,D\,X$$

Klein, Nystrand, Vogt;
Adeluyi, Bertulani;
Adeluyi, Bertulani, Murray;
Gonçalves, Bertulani



- Advantage: access to **wide range of scales** : $m_T = \sqrt{p_T^2 + m_c^2}$
- Inclusive(*) process: test of **factorization** and **universality** of PDFs
- **Charm** produced mainly in γg **fusion**
- Sensitive to the **nuclear gluon density: nuclear modification**
- **Exploring nuclear structure**

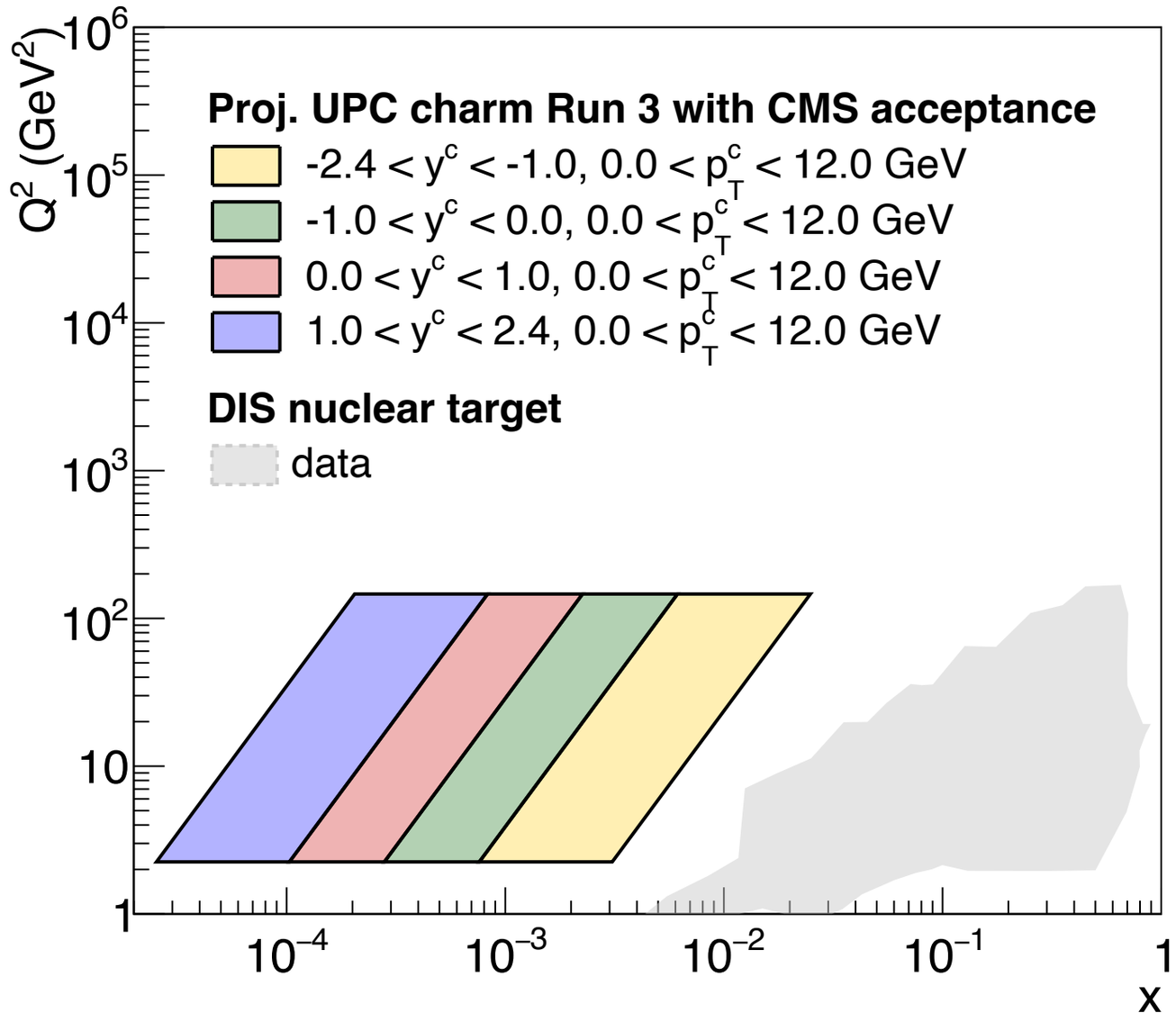
(x, Q^2) kinematic space in UPC with nuclei



LO kinematics crude estimate

$$x \sim \frac{m_T}{\sqrt{s_{NN}}} e^{-y}$$

Need $p_T < 2\,\mathrm{GeV}, y > 1$ to probe small x and Q^2 region



Charm level estimate, fragmentation shifts the estimates to higher Q^2

Cross section for charm photoproduction in FONLL

FONLL: collinear framework for **heavy flavor photoproduction and hadroproduction**
Cacciari, Frixione, Nason; Cacciari, Greco, Nason

Connects **small transverse momenta** with mass effects to the **large transverse momentum** region with logarithmically enhanced terms $\ln p_T/m$

Accurate up to NLO: $\alpha_{\rm em}\alpha_s$, $\alpha_{\rm em}\alpha_s^2$ terms exact

Includes terms up to NLL: $\alpha_{\rm em}\alpha_s(\alpha_s \ln p_T/m)^k$, $\alpha_{\rm em}\alpha_s^2(\alpha_s \ln p_T/m)^k$

Fixed order NLO

$$\frac{d\sigma}{dydp_T} = A(m)\alpha_{\rm em}\alpha_s + B(m)\alpha_{\rm em}\alpha_s^2 +$$

Resummed NLL

$$+\left(\alpha_{\rm em}\alpha_s \sum_{i=2}^{\infty} a_i(\alpha_s \log(p_T/m))^i + \alpha_{\rm em}\alpha_s^2 \sum_{i=1}^{\infty} b_i(\alpha_s \log(p_T/m))^i\right) \times G(m, p_T)$$

$$+\mathcal{O}(\alpha_{\rm em}{\alpha_s}^3(\alpha_s \log(p_T/m))^i) + \mathcal{O}(\alpha_{\rm em}{\alpha_s}^3 \times \mathrm{PST})$$

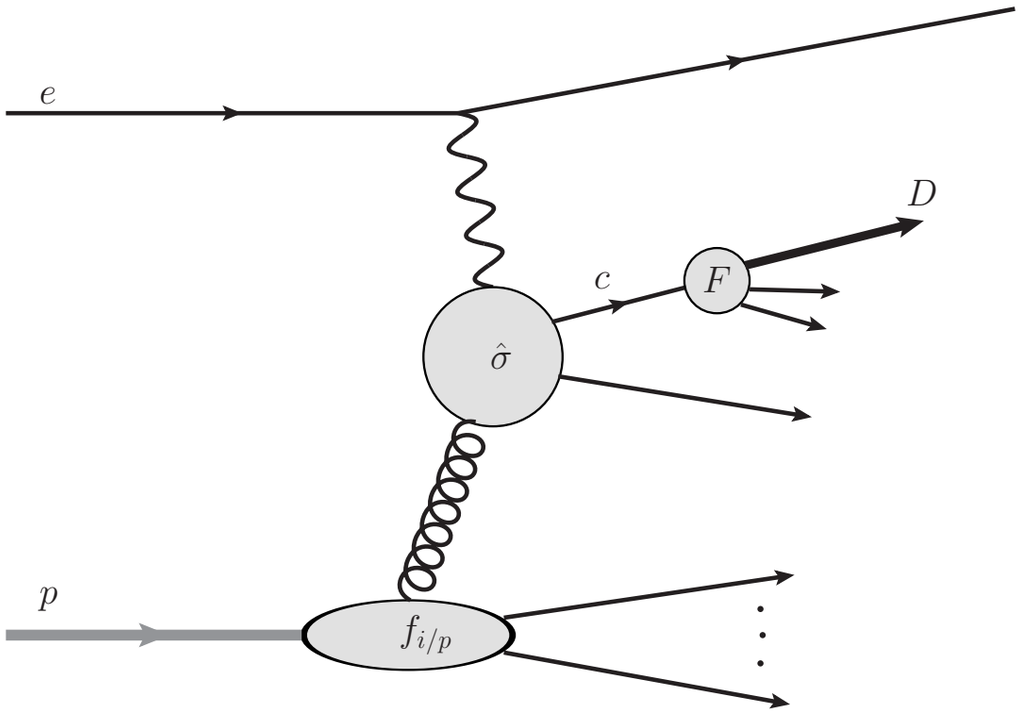
PST: power suppressed terms

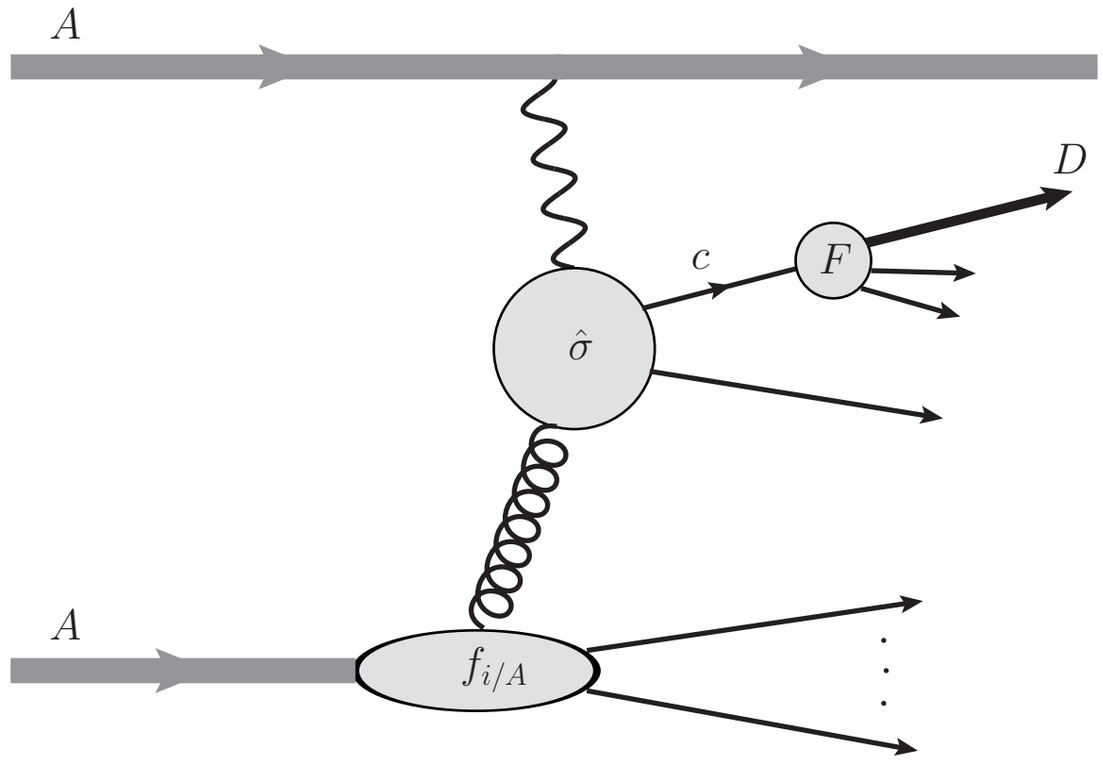
Both **direct** and **resolved** photon contribution included

$G(m, p_T)$ is regularizing function, vanishing at $p_T \to 0$, and approaching unity at large p_T

HERA ep vs LHC UPC AA

Differences between ep and UPC AA

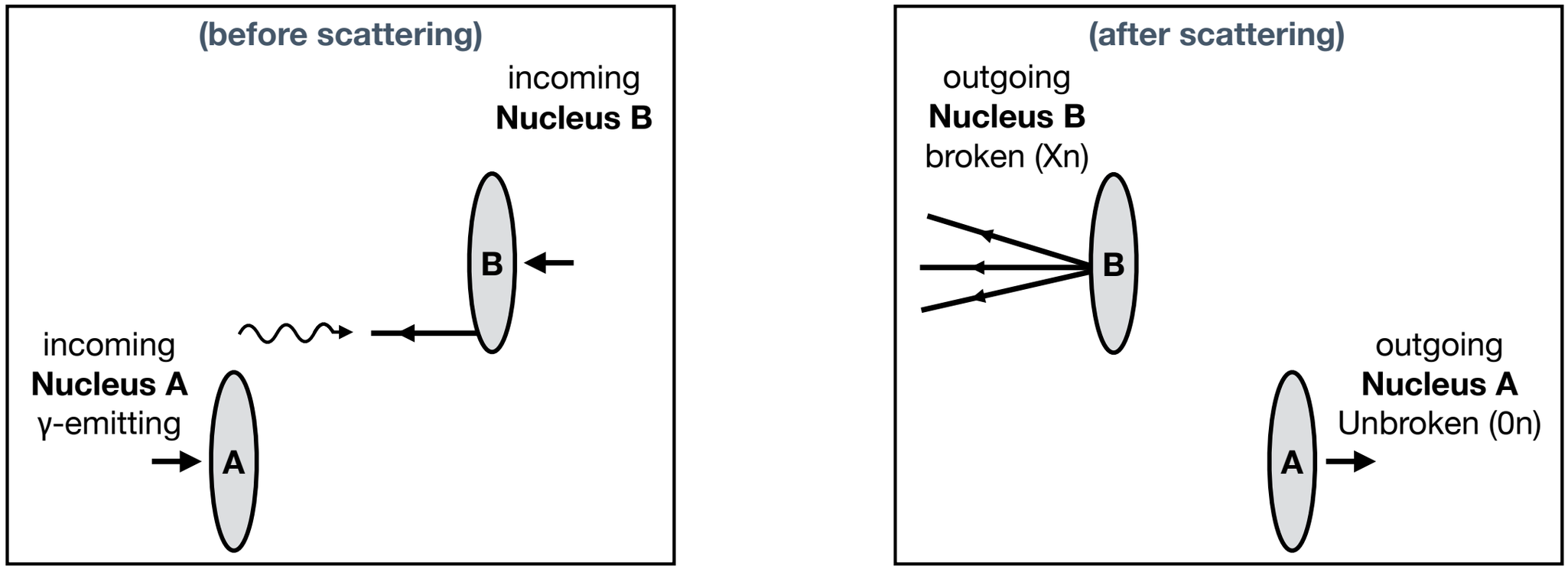




- FONLL applied to HERA data, good description of D^*
- **Electron** vs **nucleus** photon flux: different behavior
- In ep: some data sets have larger range of $Q^2 (\sim 2\,\mathrm{GeV}^2)$
- **Proton** vs **nuclear** target: **nuclear modification** expected
- In UPC : electromagnetic dissociation effect: **EMD**

UPC event selection

AA UPC: CMS selection of UPC events with **0nXn** (zero neutrons in one ZDC, at least one neutron in opposite ZDC), requires accounting for **survival probability** factor for nucleus due to possibility of **electromagnetic dissociation (EMD)**



In UPC **0nXn** selection means (part of) **coherent diffraction** is rejected.
In theoretical calculation it is included: **inclusive** process
Estimate from Frankfurt-Guzey-Strikman model: ~ 10 %

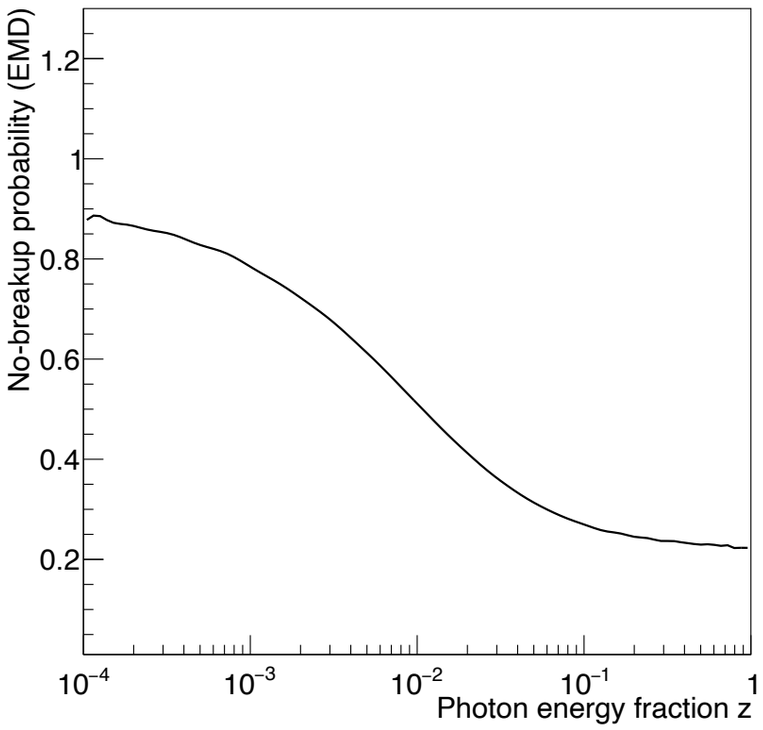
Electromagnetic dissociation in UPC

- **0nXn** requirement means photon-emitting nucleus left unbroken
- Additional EM interactions can lead to break-up of nucleus
- Effective flux: fold the survival probability, assuming factorization of hard interaction and soft-excitation probability

STARLIGHT

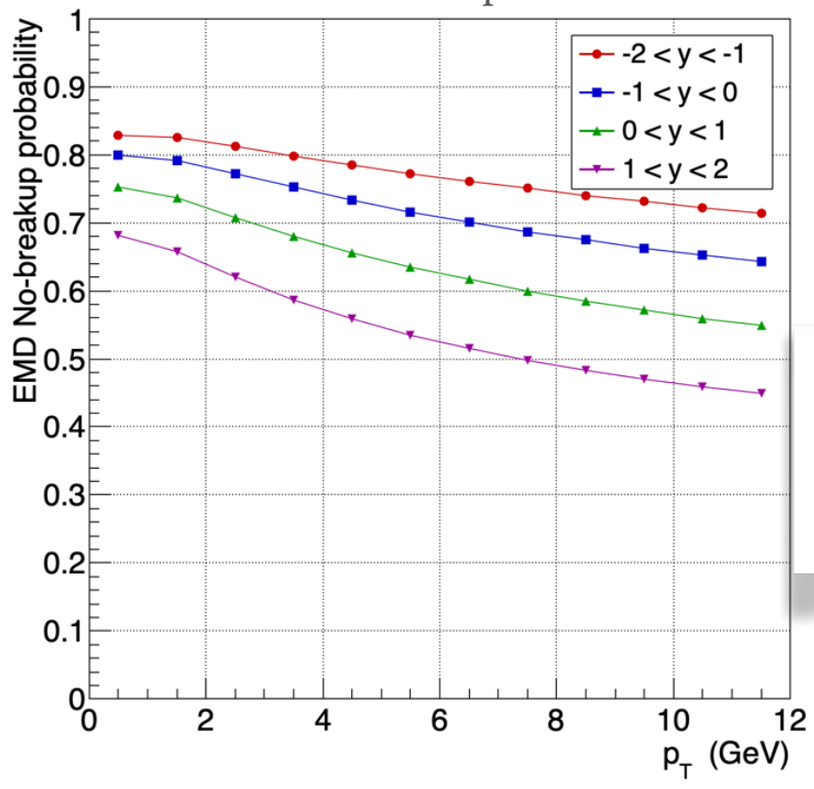
$$f^{\text{eff}}_{\gamma/A}(z) \;=\; \int d^2\mathbf{b}\, P_{\text{no EM}}(\mathbf{b})\; \tilde{f}_{\gamma/A}(z,\mathbf{b})\; \theta(|\mathbf{b}| - b_{\text{min}})$$

Ratio of effective photon flux to no-break up photon flux



Eskola, Guzey, Helenius, Paakkinen, Paukkunen

Ratio of D0 cross section with and w/o breakup



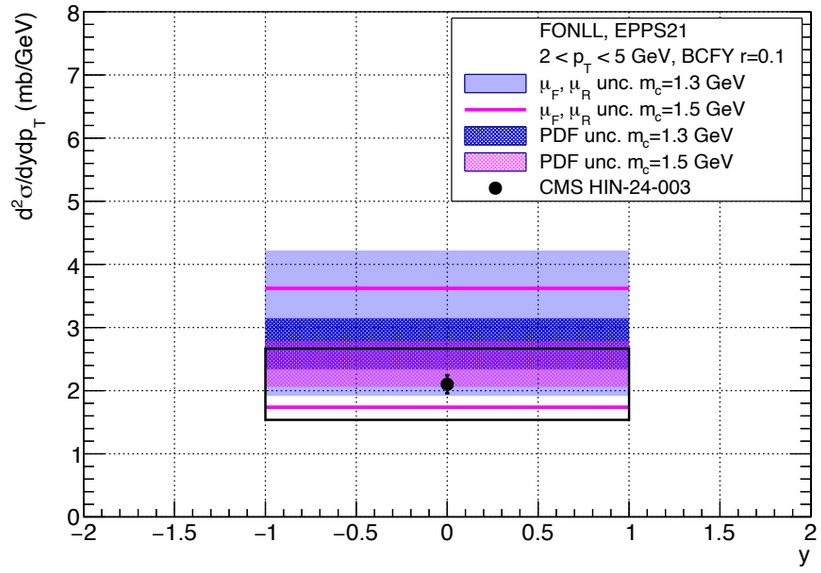
EPPS21 PDF
BCFY FF
$m_c = 1.3\,\text{GeV}$

Large reduction: 0.8 to 0.4

Comparison of GγA-FONLL with CMS data on D^0

$Pb(\gamma)$ ⟶ ⟵ $Pb(g)$

Data: CMS PAS HIN-24-003



Cross section: FONLL

GγA-FONLL: Generalized photon-nucleus FONLL

nPDF: EPPS21

Photon flux: EMD included

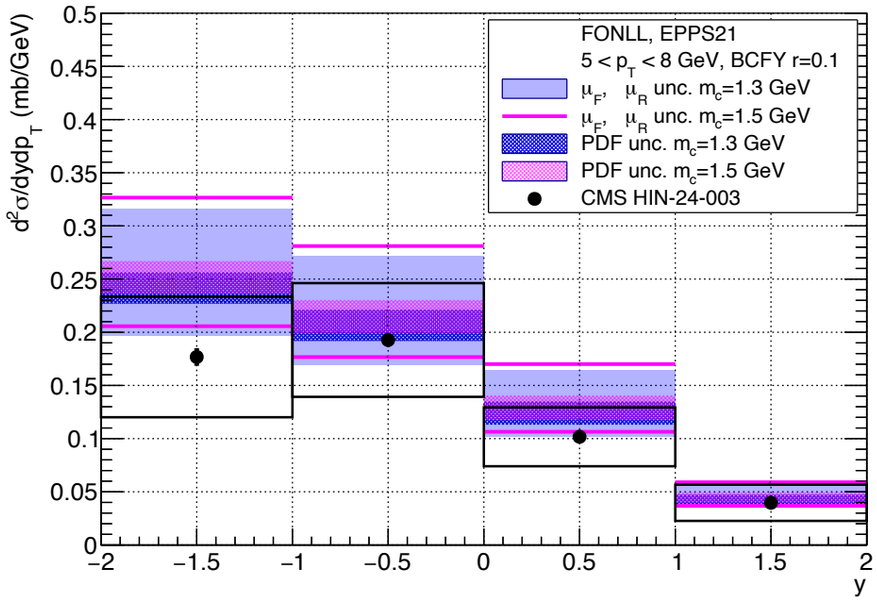
Fragmentation: BCFY, r=0.1 $m(D^0) = 1865\,\text{MeV}$

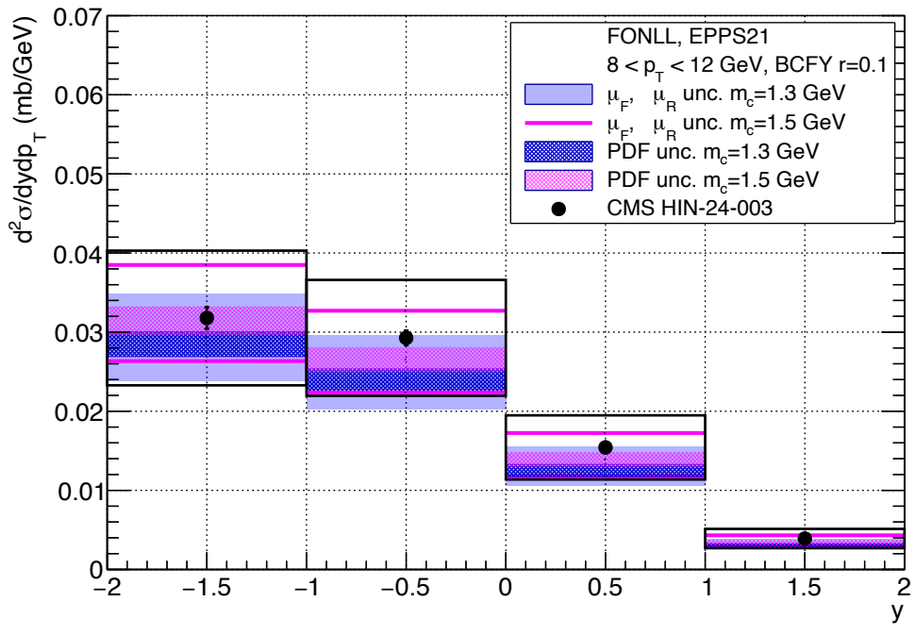
Lighter bands/lines :

Scale variation: μ_f/m_T, $\mu_r/m_T(0.5,1,2)$, $\frac{1}{2} \leq \mu_f/\mu_r \leq 2$

Darker/smaller bands: PDF uncertainty

$m_c = 1.3,1.5$ GeV





Comparison of FONLL with CMS data

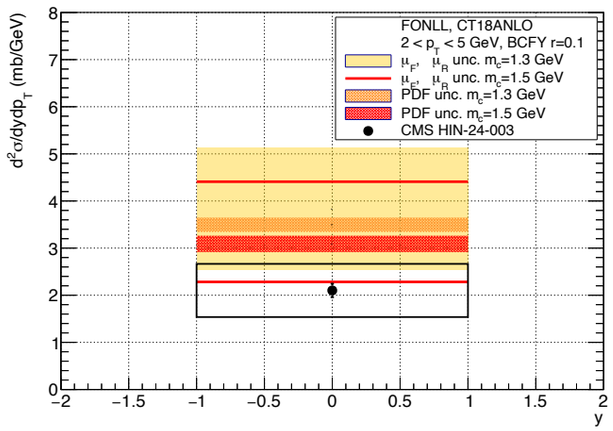
Reasonable agreement within the theoretical/ experimental uncertainties

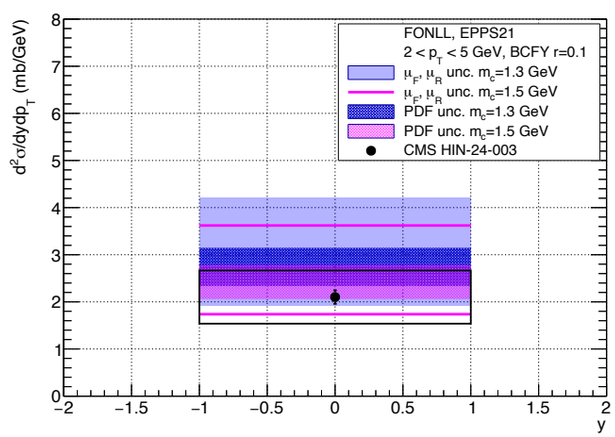
Cacciari, Innocenti, AS, arXiv:2506.09893

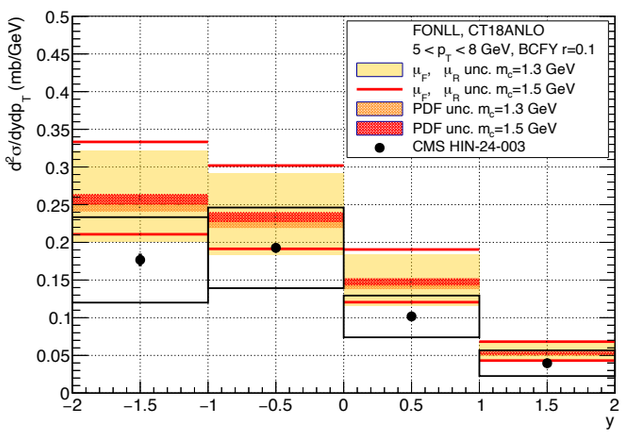
Comparison of GγA-FONLL with CMS data on D^0

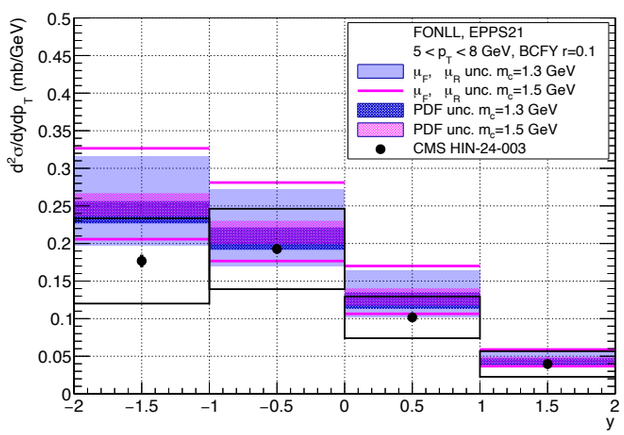
proton PDF

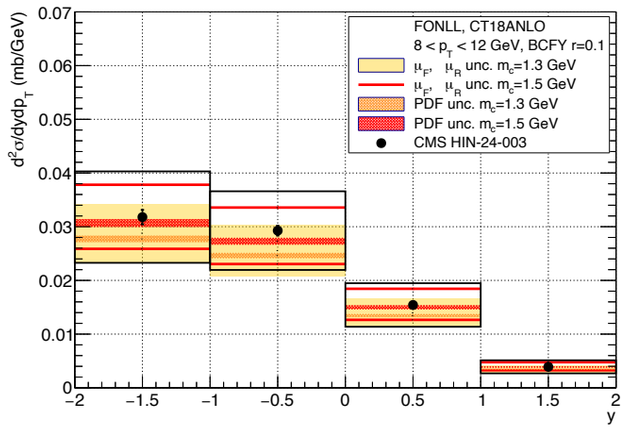
lead PDF

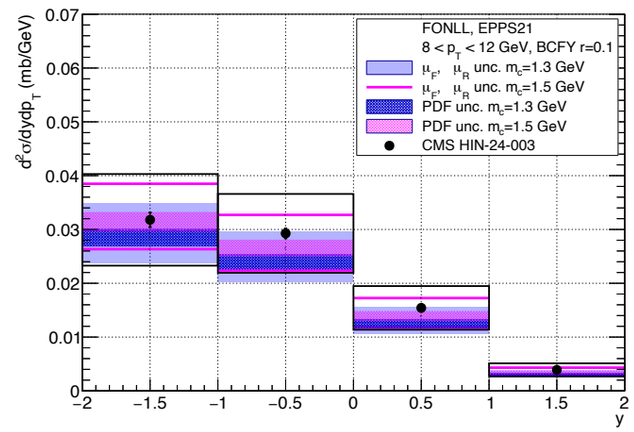












Testing nuclear effects:

proton vs *lead* PDF

Comparison of proton vs nuclear PDF

CT18ANLO vs EPPS21 Pb

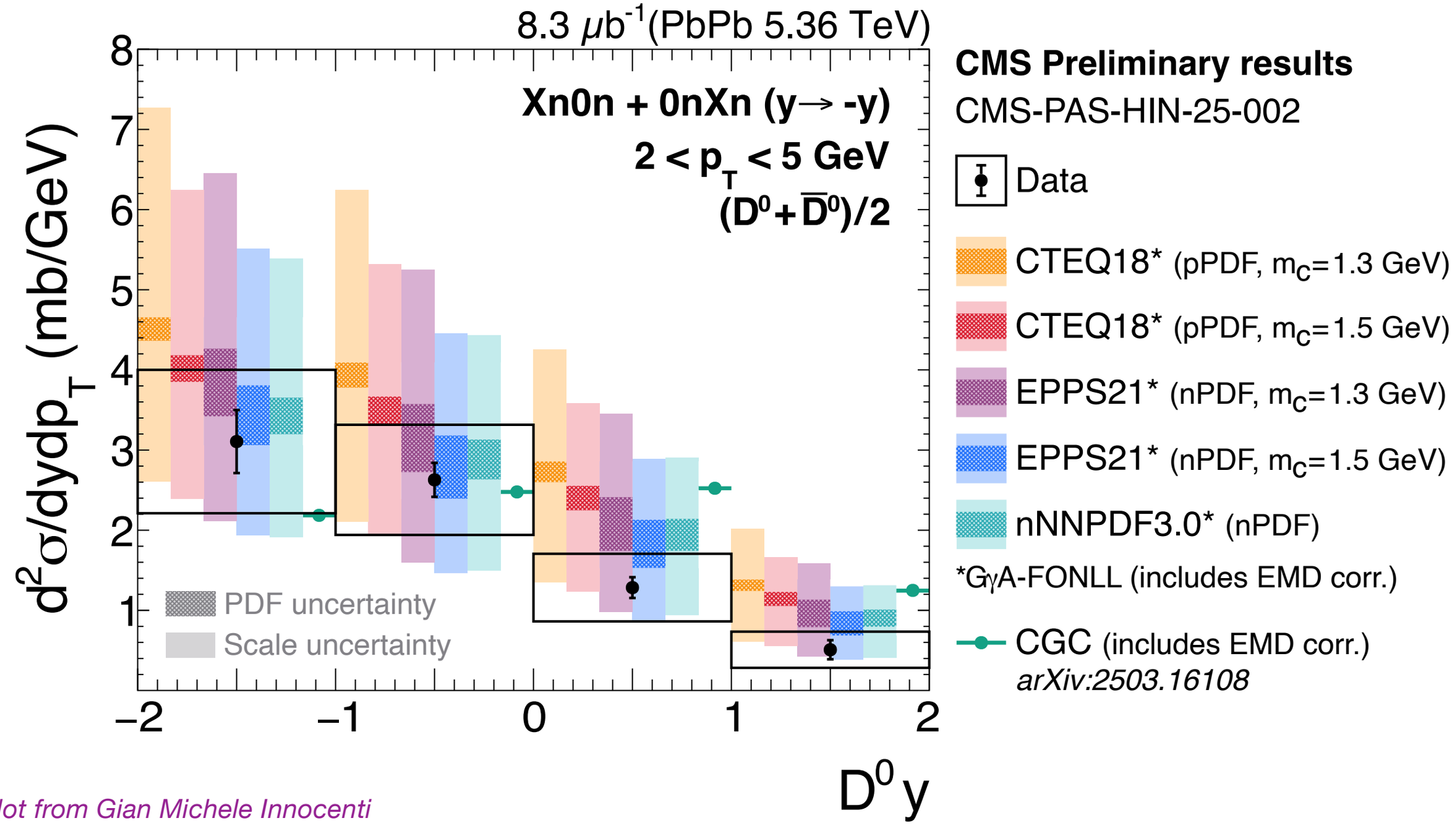
Nuclear modification largest for

$2 < p_T < 5$ GeV

CMS data vs theoretical calculations

Bands:

Scale variation: μ_f/m_T, $\mu_r/m_T(0.5,1,2)$



Plot from Gian Michele Innocenti

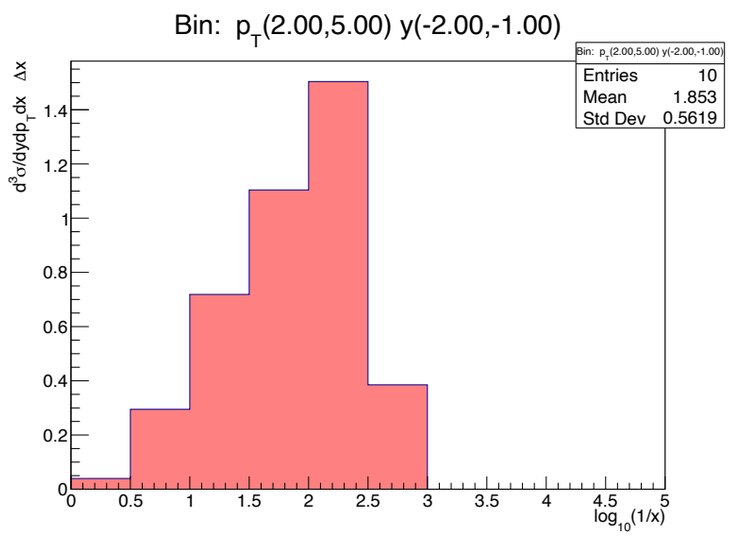
Typical x_g contributing to the cross section

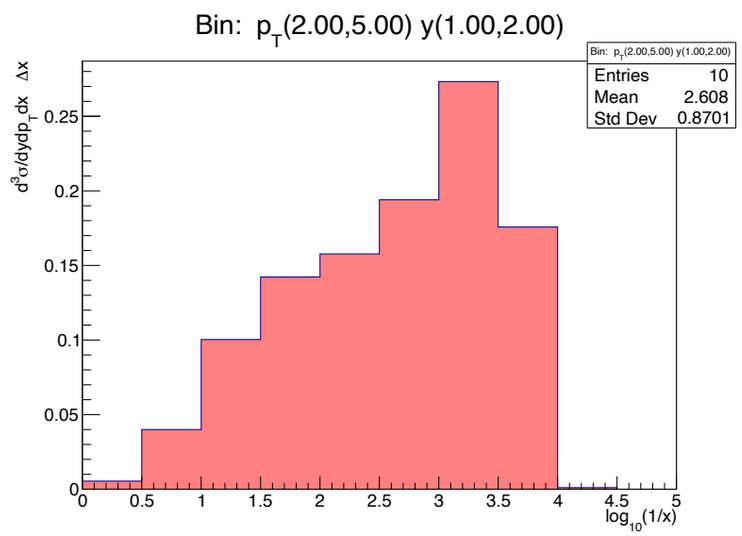
Can calculate exactly the distribution of typical values of x in each pT and y bin

negative y

positive y

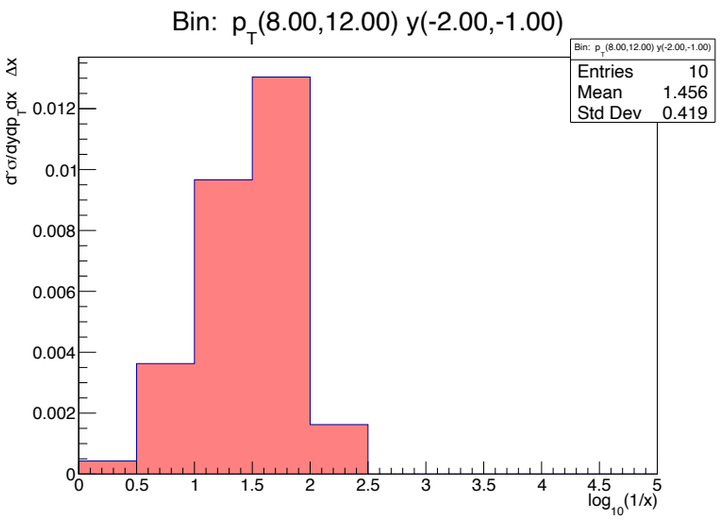
low p_T



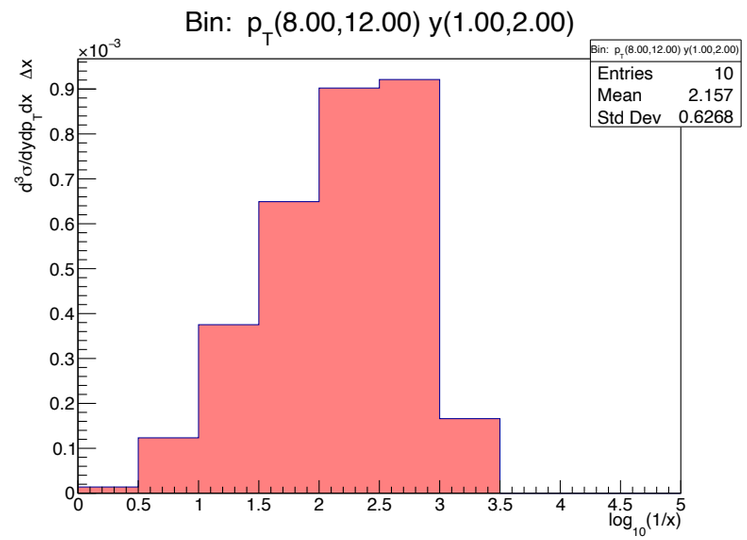


smallest x: $10^{-3} - 10^{-4}$
mean: 2.5×10^{-3}

high p_T



largest x: $10^{-1} - 10^{-2}$



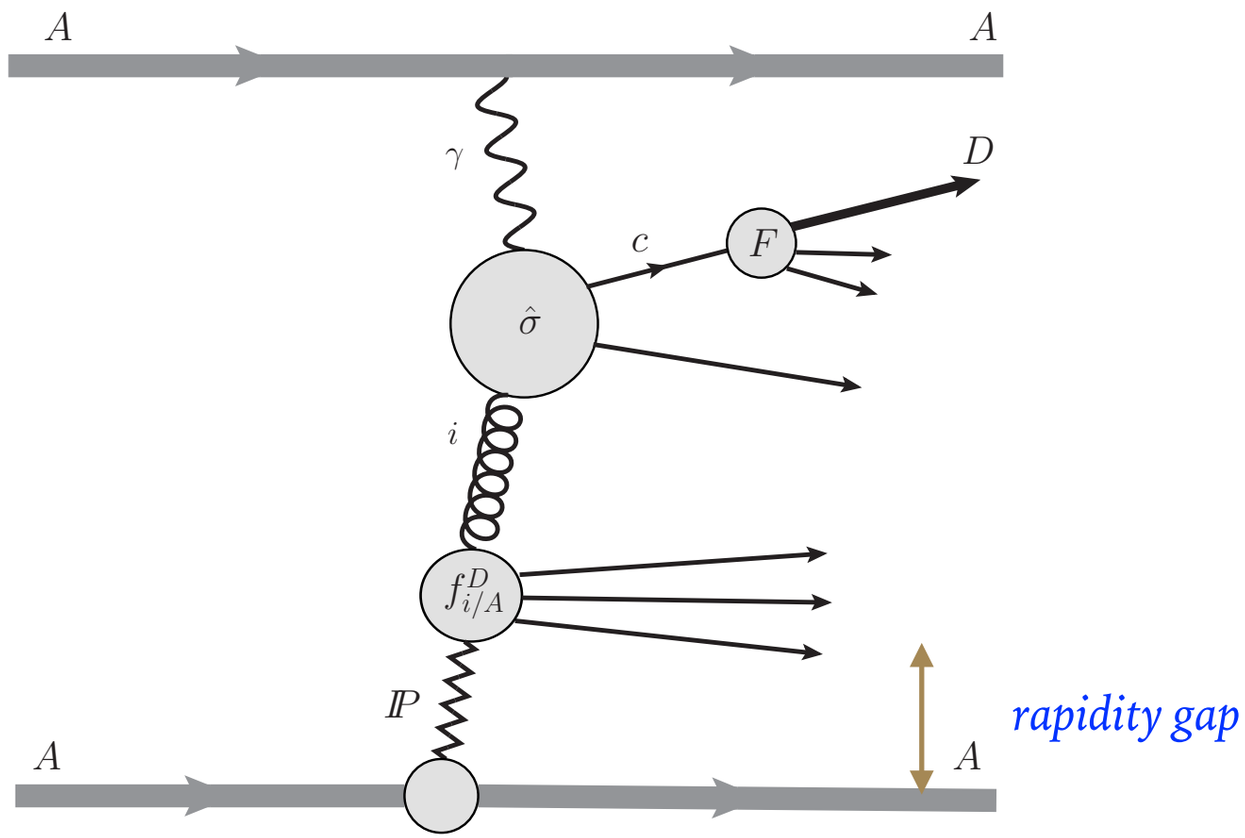
Diffractive charm photoproduction in UPC

Additional variables for diffraction:

β momentum fraction of parton w.r.t Pomeron

$\xi = x_{I\!P}$ momentum fraction of the Pomeron w.r.t hadron

t momentum transfer squared (at the proton vertex)

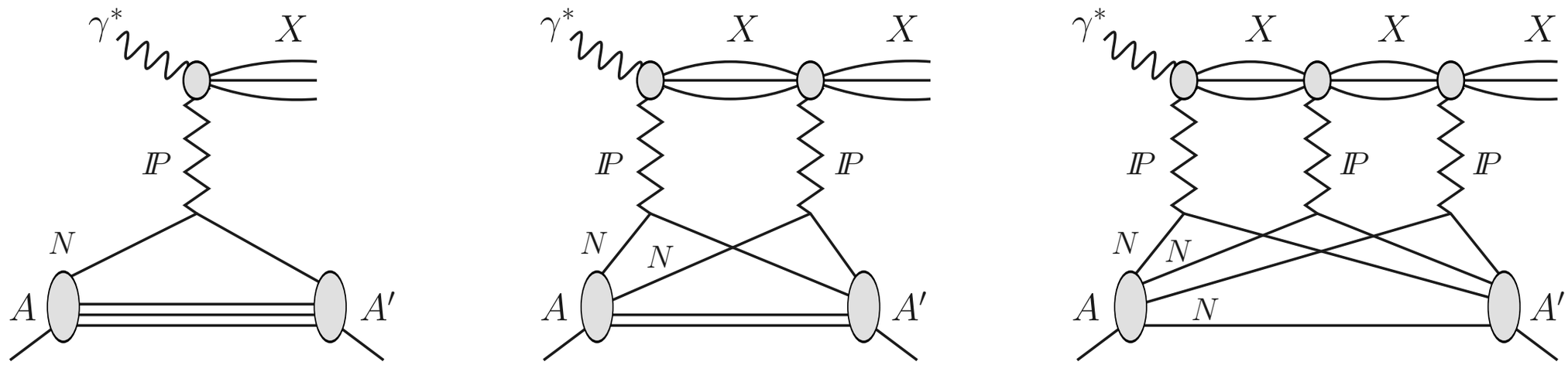


- Diffractive parton distributions were used to compute the diffractive **photoproduction** of **charm** and comparison with data at HERA
- Use collinear framework to evaluate the **diffractive charm contribution in UPC**
- Proton **diffractive PDFs** available from HERA.
- Need diffractive parton distributions in **nuclei**

Diffraction in nuclei

Leading Twist Approach (LTA) for nuclear shadowing *Frankfurt, Guzey, Strikman*

- Based on proton diffractive PDFs
- Include nuclear shadowing through multiple scattering of diffractive states



diffractive scattering on a nucleon

soft rescattering on remaining nucleons

$$\Gamma_{\gamma^* A\to X A'}(\vec{b}) = \langle A'|\sum_i^A \Gamma_{\gamma^* N\to X N}(\vec{b}-\vec{r}_{i\perp}) e^{iz_i\Delta_{\gamma^* X}} \prod_{j\neq i}\Big(1-\theta(z_j-z_i)\Gamma_X(\vec{b}-\vec{r}_{j\perp})\Big)|A\rangle$$

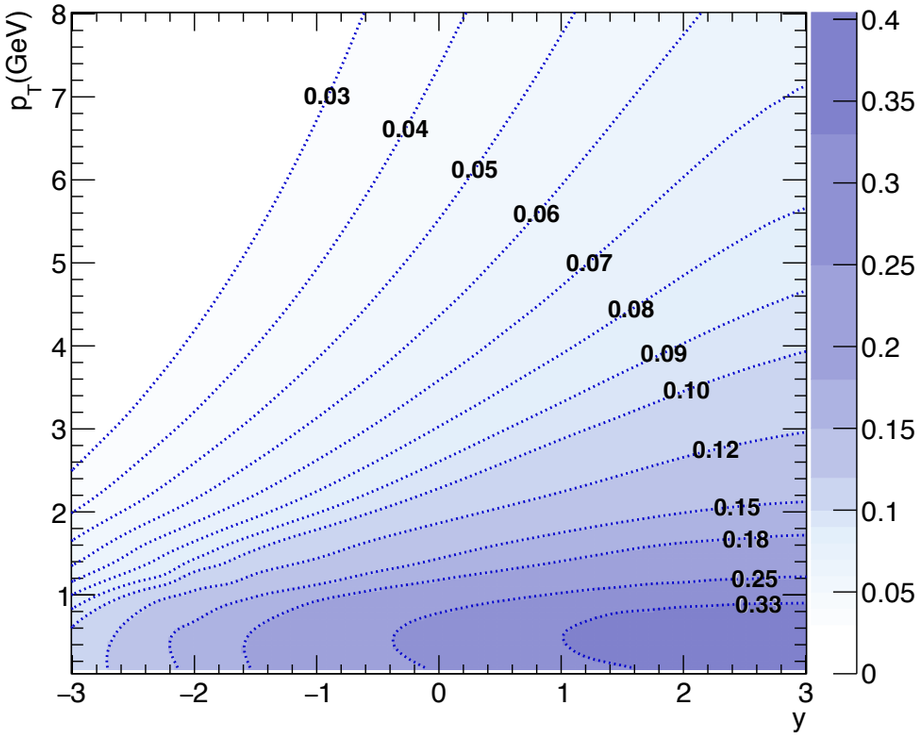
Extract diffractive parton density in the nucleus $f_{i/A}^{D(3)}(\xi, z, \mu^2)$

Diffractive contribution to charm production in UPC

Ratio of diffractive to inclusive for cross section of D^0 meson photoproduction in UPC AA:two limits of LTA model

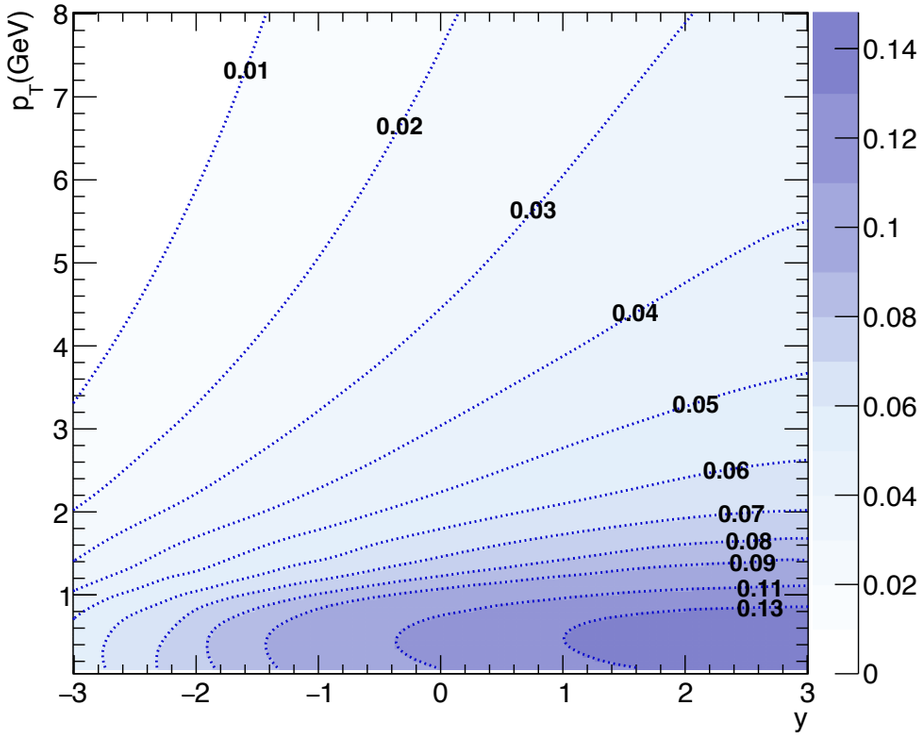
transverse momentum

LTA High



LTA Low

Guzey, Innocenti, AS, Strikman

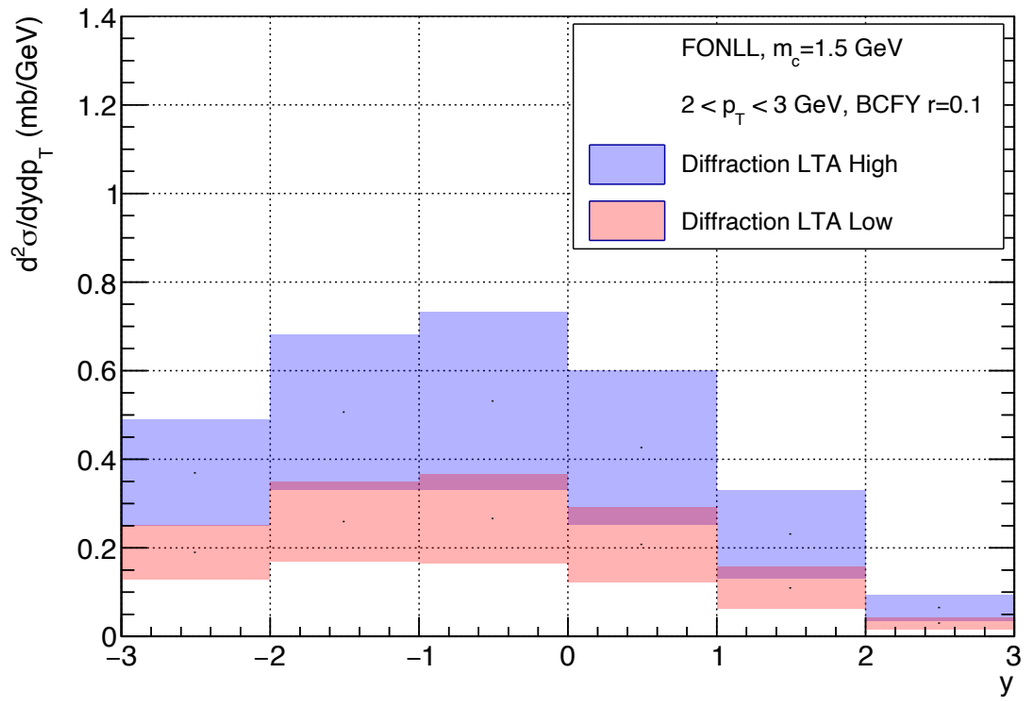


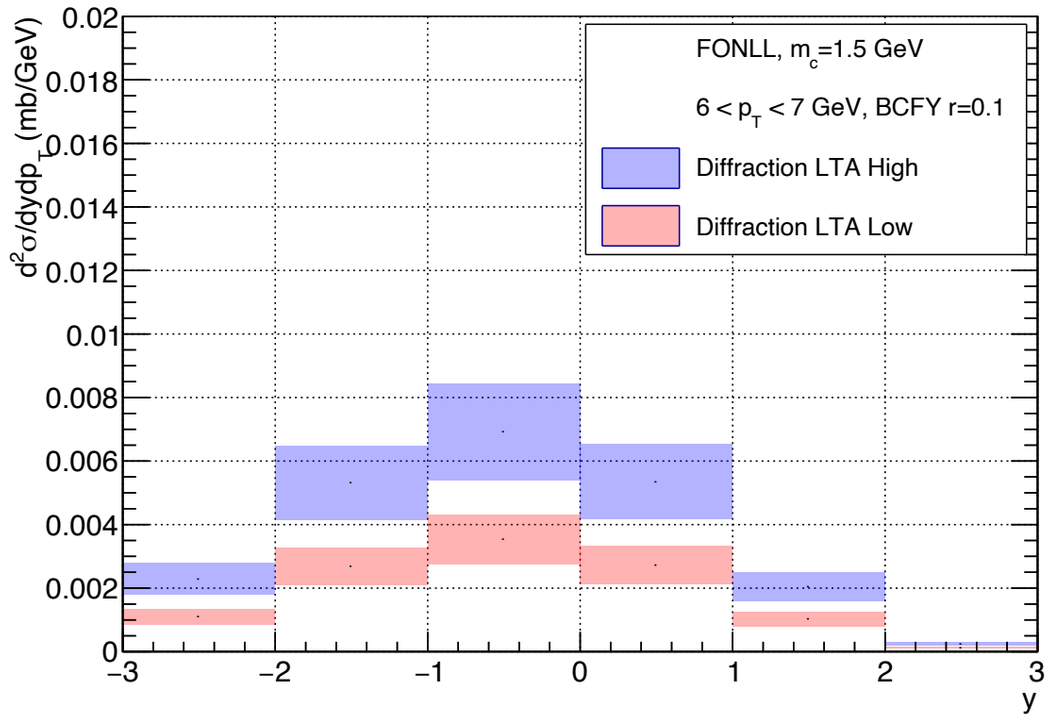
rapidity

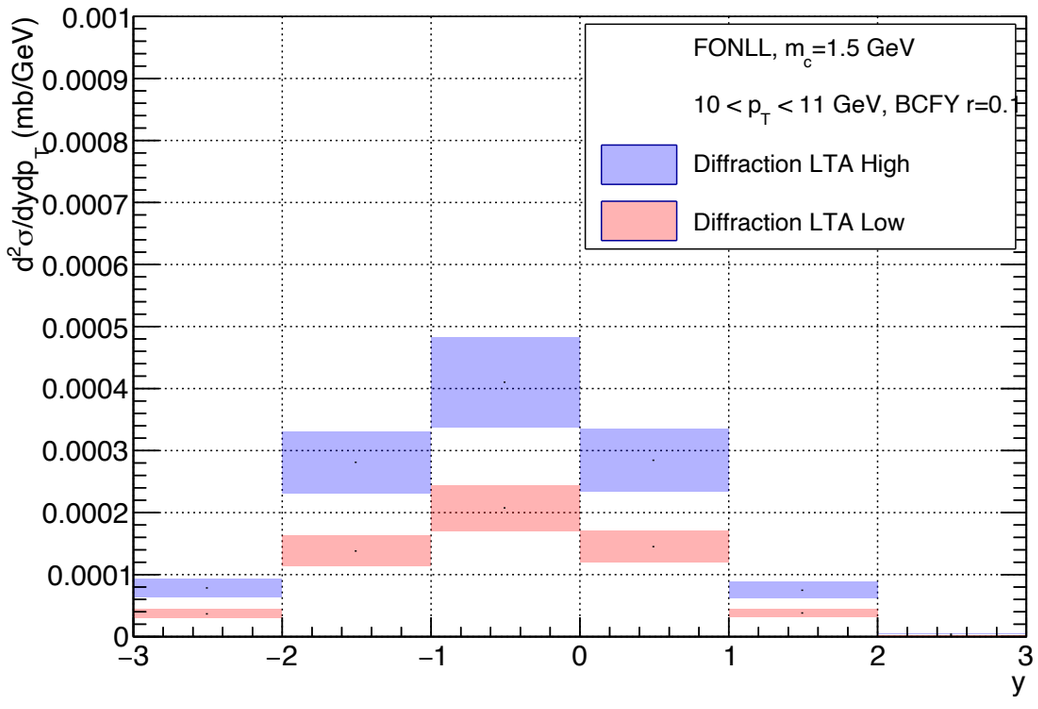
integrated over $x_{I\!P} < 0.1$

Coherent diffractive contribution below 10%, for $p_T > 3$ GeV

Diffractive cross section in UPC AA







Bands:

Scale variation:

$$\mu_f/m_T,\ \mu_r/m_T(0.5,1,2),\ \frac{1}{2} \le \mu_f/\mu_r \le 2$$

Diffractive cross section in AA evaluated in collinear approach with LTA approach

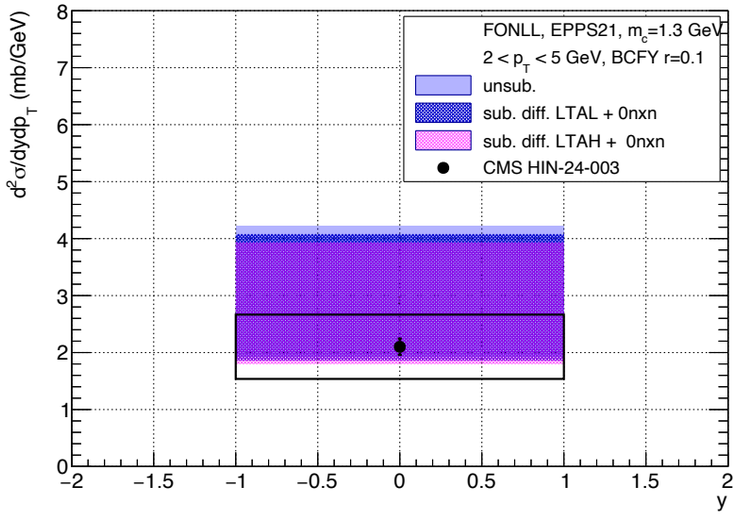
Diffraction is more suppressed at negative y

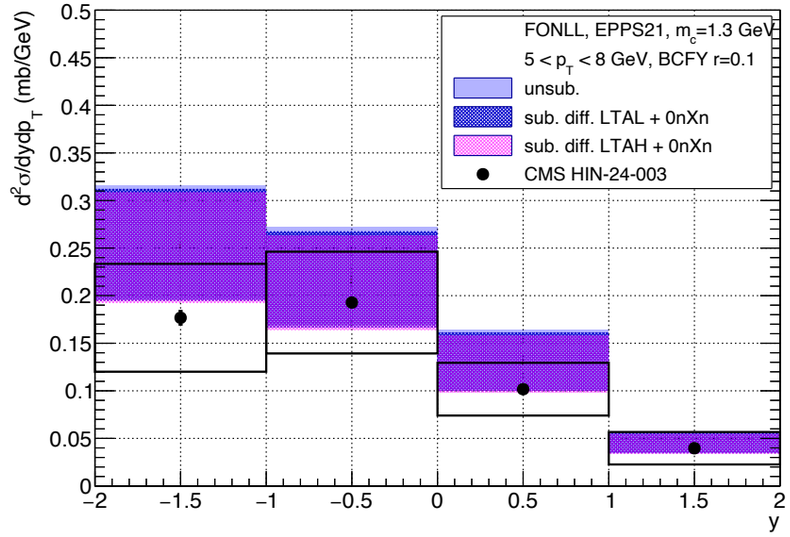
10% contribution at small p_T bin

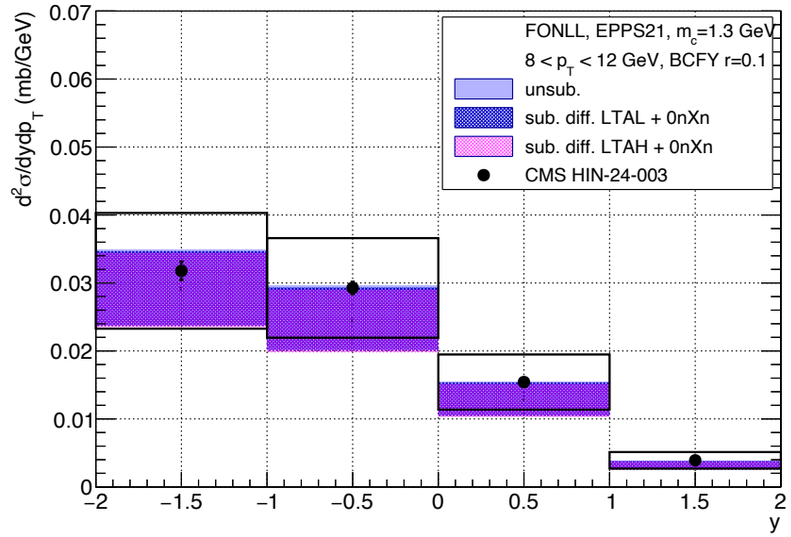
Corrected calculation: subtracting part of diffraction

Subtracting part of diffraction to account for 0nXn experimental condition

$$\frac{d^2\sigma}{dydp_T} = \mathcal{R}^{EMD}(\frac{0nAn}{AnAn})(\frac{d^2\sigma^{incl}}{dydp_T} - \frac{d^2\sigma^{diff}}{dydp_T}) + \mathcal{R}^{EMD}(\frac{0nXn}{AnAn})\frac{d^2\sigma^{diff}}{dydp_T})$$







Corrected predictions with subtracted coherent diffraction:

minimal change, largest effect for lowest pT

Diffractive and inclusive contributions in proton–nucleus

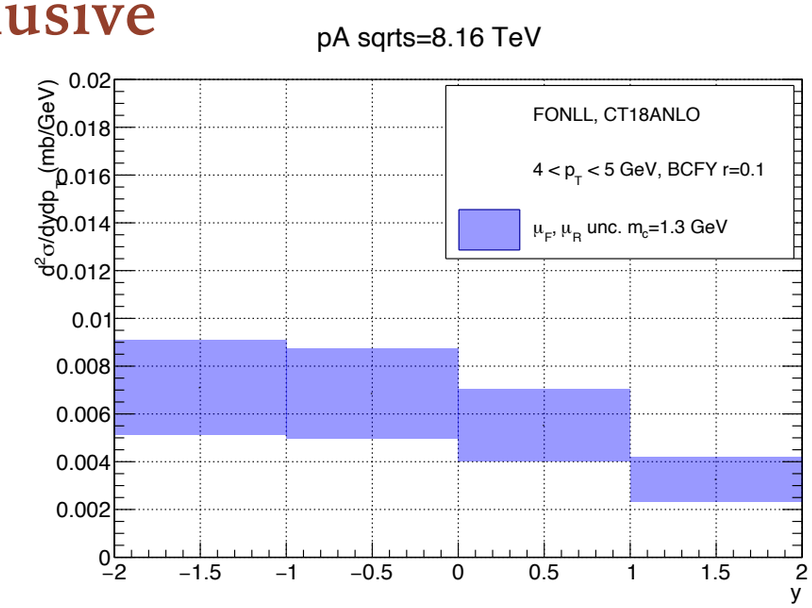
Predictions for inclusive and diffractive charm photoproduction for proton-nucleus

In pA UPC we assume the photon source is the nucleus: $\gamma + p \to D^0 + X$

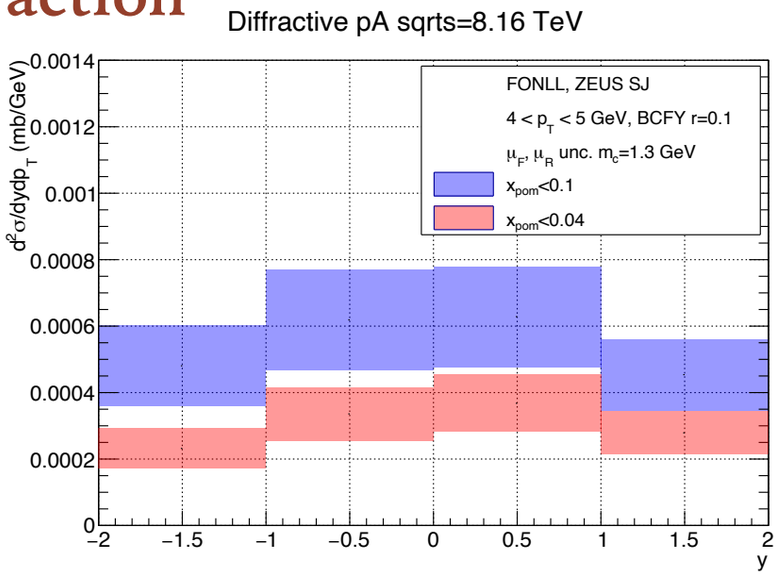
Diffractive PDFs from proton fitted to HERA: ZEUS SJ set

Energy: $\sqrt{s} = 8.16$ TeV, $E_p = 6.5$ TeV, $E_{Pb/A} = 2.56$ TeV

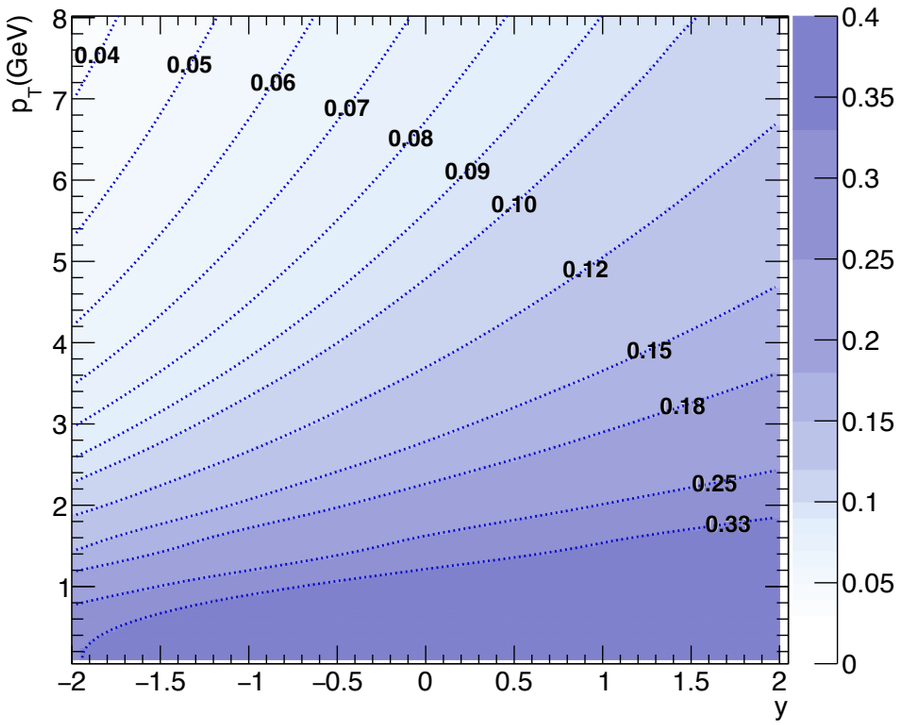
inclusive



diffraction



diffractive ratio in pA



integrated over $x_{I\!P} < 0.1$

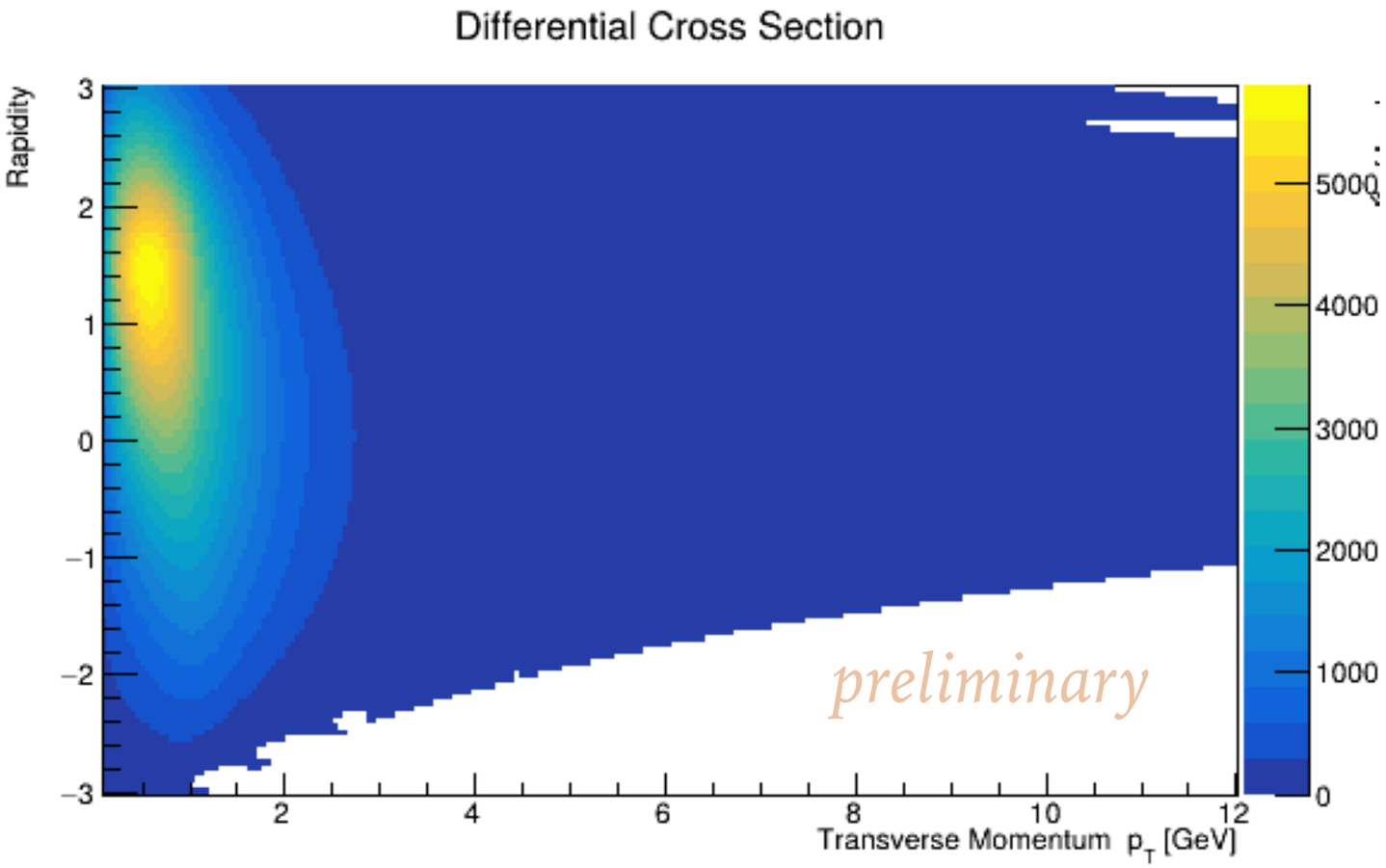
In UPC pA: charm photoproduction process to explore proton structure

Predictions for EIC

Predictions for inclusive charm photoproduction for the EIC.

EPPS21, D^0, Au, $\sqrt{s} = 90$ GeV

$$\frac{d^2\sigma}{dydp_T}(\text{pb/GeV})$$



A is going into positive y

photon fraction between 0.01 and 0.95

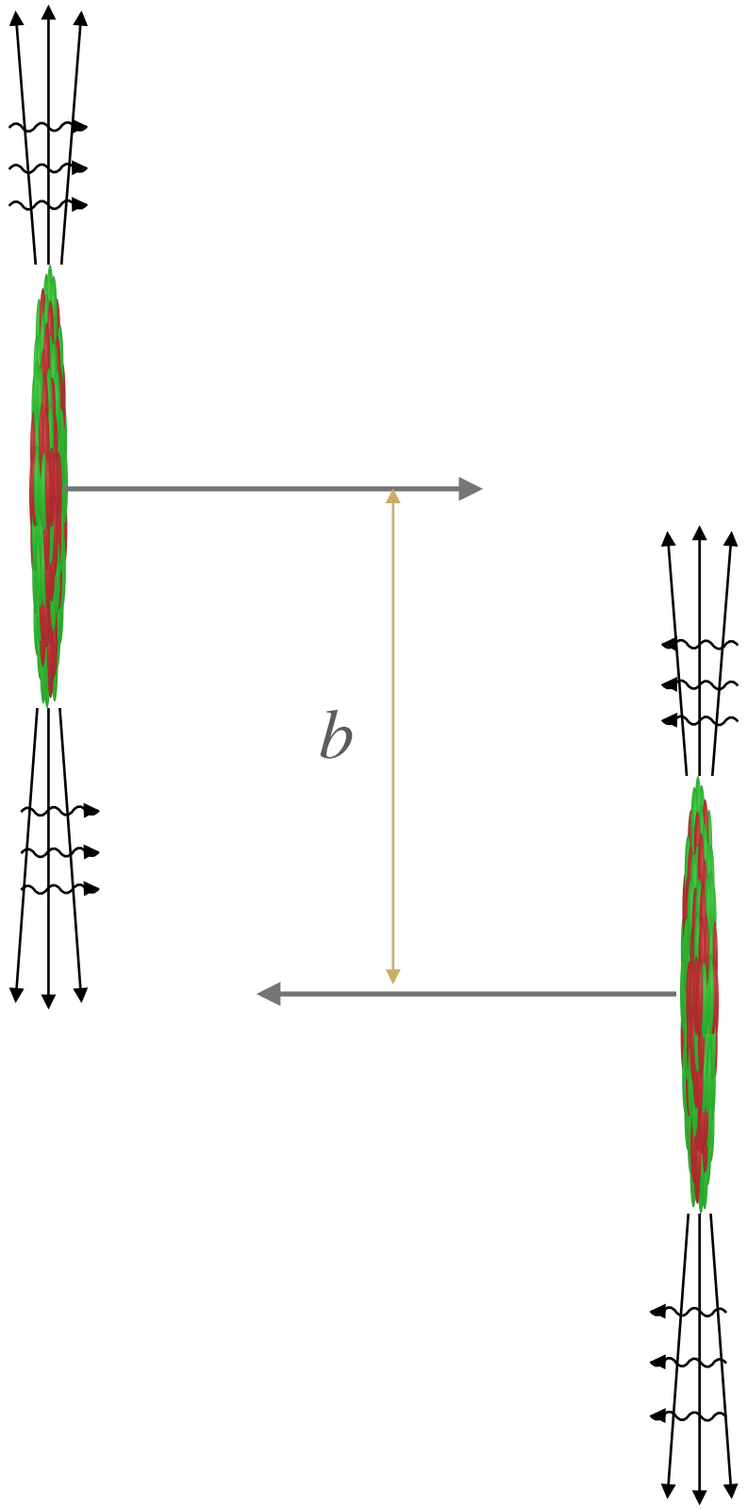
$Q^2_{cut} = 0.01$ GeV^2

Summary and outlook

- **GγA-FONLL** prediction on **open charm photoproduction in PbPb UPC at LHC**, $\sqrt{s_{\mathrm{NN}}} = 5.36\,\mathrm{TeV}$
- **UPCs**: **EMD** leads to the **reduction** of cross section by **0.8-0.4** in the CMS kinematics
- **Reasonable agreement** between theory and data on **D^0 production from CMS**, within theoretical and experimental uncertainties
- Effects of **nuclear modification visible** in the CMS kinematics, at low p_T
- CMS data at **low p_T** (differential in rapidity) may point to **stronger nuclear** modification than currently encoded in the current nPDFs, however more detailed studies needed to disentangle various effects
- **Diffractive** cross section in **UPC AA** was evaluated using collinear factorization with **LTA** diffractive fraction about 10-15% in the lowest transverse momentum and highest rapidity bin. Such measurement could be used to constrain **nuclear diffractive PDF**
- Predictions for **UPC pA**, inclusive and diffractive.
- **Outlook**: inclusive and diffractive charm production at the **EIC**

Backup

Ultraperipheral AA collisions



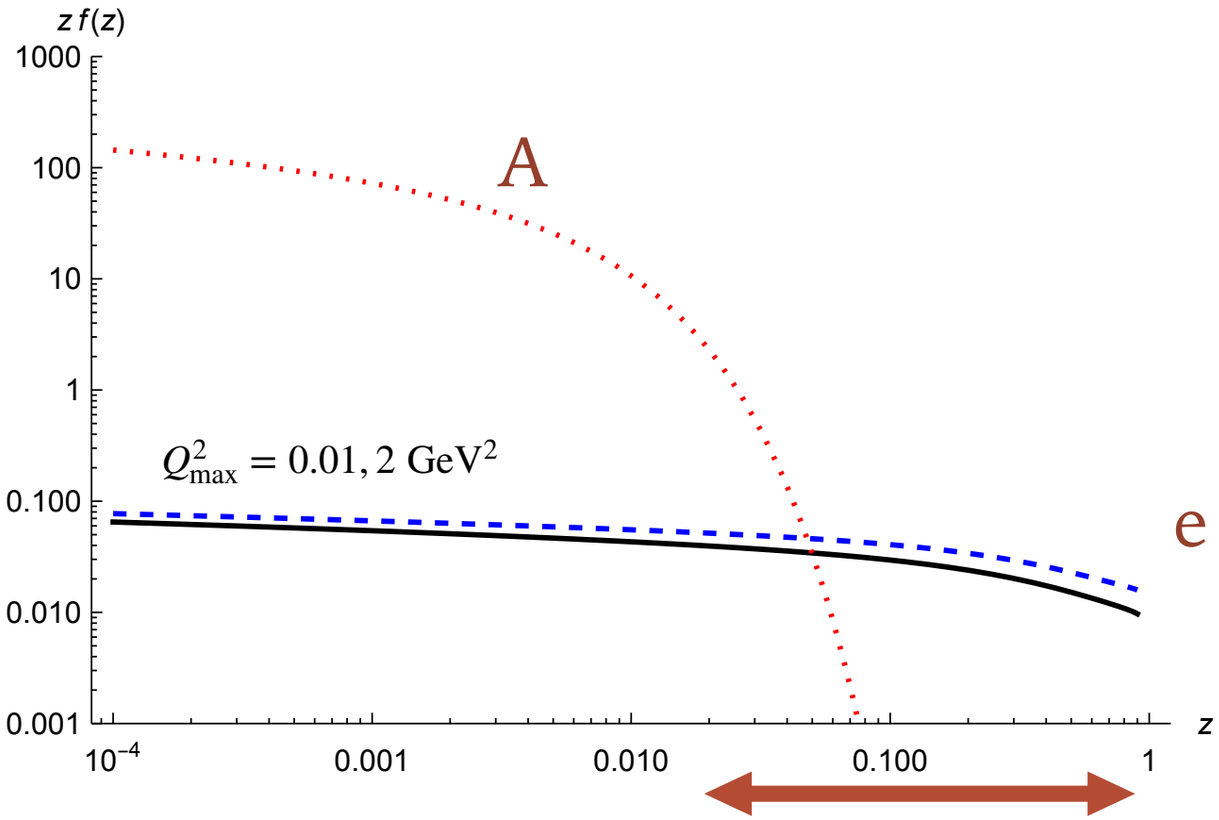
- UPC: **ultraperipheral** AA collisions, $b > 2R_A$
- Dominated by **electromagnetic** component
- **Cleaner environment** than standard AA collisions
- Equivalent photon approximation EPA
- Photon flux **enhanced** by Z^2 of nucleus
- Unique source of **high-energy photon-nucleus** collisions
- **AA collider as a γA or $\gamma\gamma$ collider !**

LHC :

PbPb, Z=82, A=208

$\sqrt{s_{\mathrm{NN}}} = 5.36\,\mathrm{TeV}$

Photon fluxes for electron and nucleus



Comparison with **electron** flux

HERA (electron-proton) photon energy, extending to large fractions

UPC: flux steeply falling beyond z=0.01

electron

$$f_{\gamma/e}(z) = \frac{\alpha_{em}}{2\pi}\left[\frac{1+(1-z)^2}{z}\log\left(\frac{Q^2_{\max}(1-z)}{(m_e z)^2}\right) + 2m_e^2 z\left(\frac{1}{Q^2_{\max}} - \frac{1-z}{(zm_e)^2}\right)\right]$$

Improved flux:
Frixione, Mangano, Nason, Ridolfi

nucleus

$$f_{\gamma/A}(z) = \frac{2Z^2\alpha_{em}}{\pi z}\left[\eta K_0(\eta)K_1(\eta) - \frac{\eta^2}{2}(K_1(\eta)^2 - K_0(\eta)^2)\right]$$

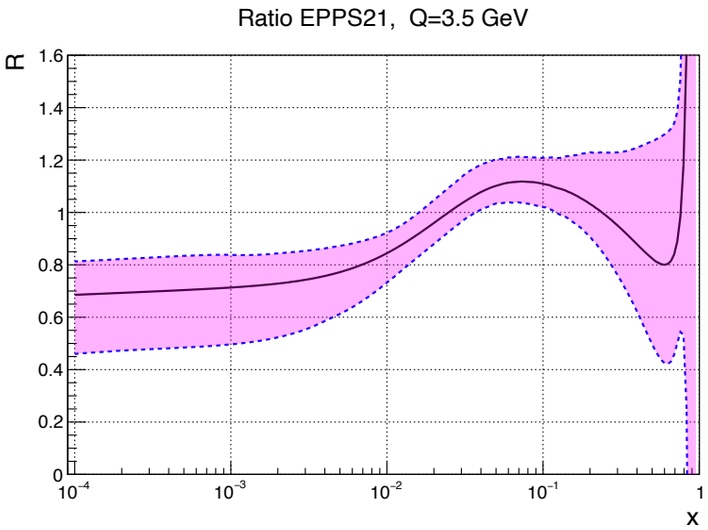
$$\eta = z m_p b_{\min}/(\hbar c)$$

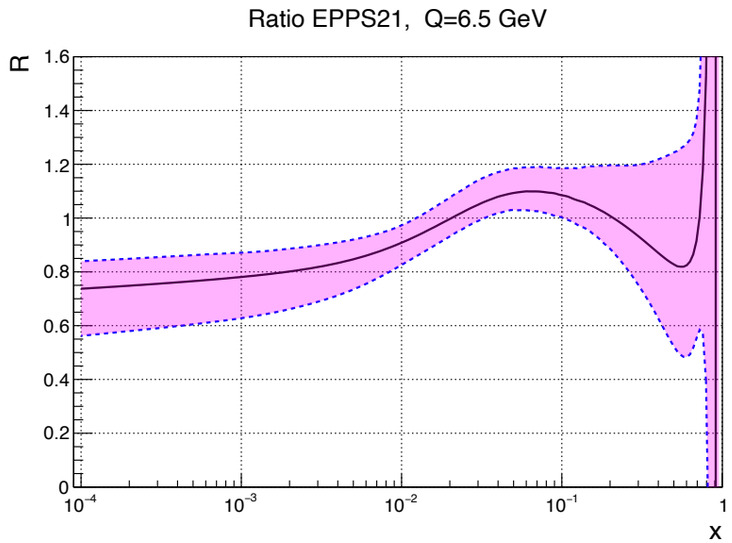
$$Z = 82,\ b_{\min} = 2R_A = 2\times 7.1\ \mathrm{fm}$$

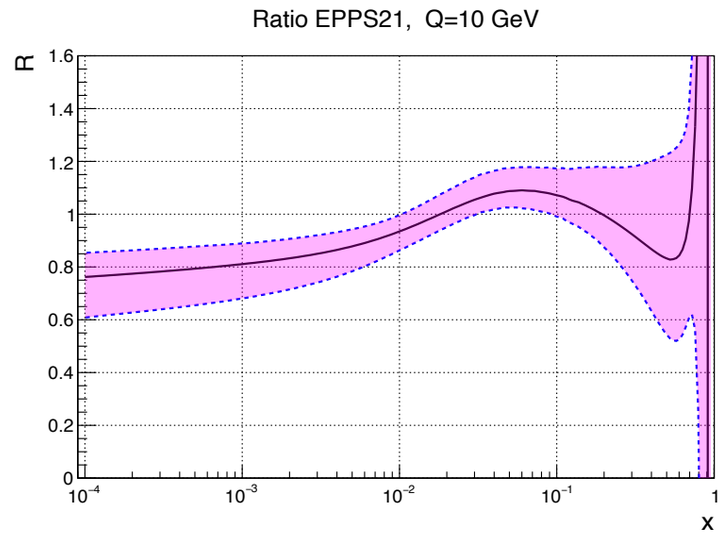
Nuclear gluon distribution: shadowing effects

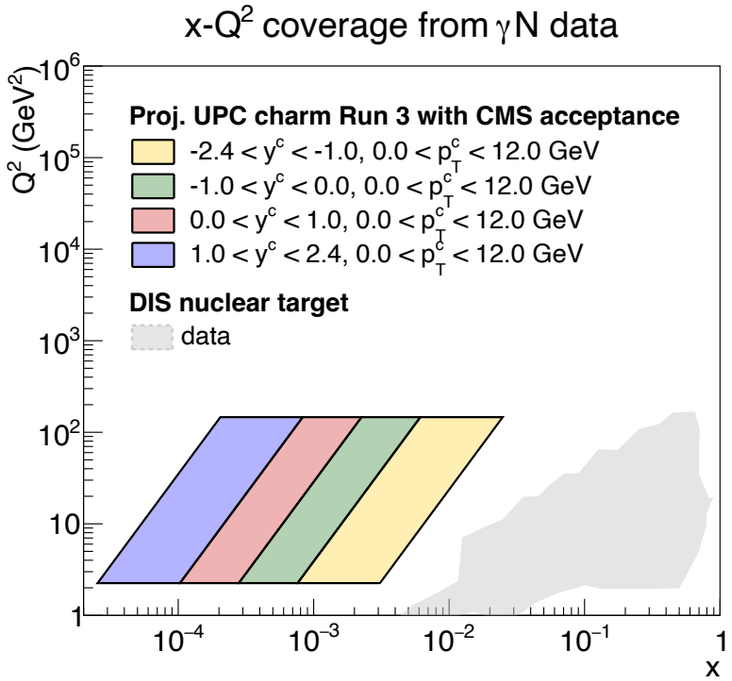
Nuclear ratios for gluon EPPS21 evaluated at the middle of the pT bins

(2,5), (5,8), (8,12)







Shadowing ratio at about 70% for lowest p_T bin and low x, evaluated at the gluon(parton) level

Reduction visible in lowest p_T bin in CMS measurement, seems stronger than the nPDFs